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Comparison of Opacity Measurements by
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16. ABSTRACT Measurements of opacity of particulate emissions by trained observer and by in-stack transmissometer were compared on 26 different occasions at 17 different stacks and 13 different plants to see how well these two commonly used methods would agree when applied to real plants under field conditions. During the study opacities ranging from 2 percent to 57 percent were measured. The high opacities were usually obtained by reducing the efficiency of particulate control devices. The data were compared with the standard of ± 7.5 percent opacity deviation between observer and transmissometer, used to certify observers of training plumes. Both measurements were within the ± 7.5 percent opacity range of agreement for 19 of the tests (73 percent of the time). The observer measurements exceeded the transmissometer measurements by more than 7.5 percent opacity in 3 tests (12 percent of the time), and were below the range in 4 tests (15 percent of the time). Two of the three higher observer readings were attributed to the condensibility of the plumes being measured, and one was attributed to interference by a nearby plume. Two of the low observer readings were attributed to adverse viewing conditions. The reason for the two other low opacity measurements was not apparent. In general, agreement of ± 10 percent opacity may be expected between observer and transmissometer measurements when observer measurements are at the stack exit and ambient conditions permit good visibility of plume.		
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Comparison of Opacity Measurements by Trained Observer and In-Stack Transmissometer

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Measurements of opacity of particulate emissions by trained observer and by in-stack transmissometer were compared on 26 different occasions at 17 different stacks and 13 different plants to see how well these two commonly used methods would agree when applied to real plants under field conditions. During the study opacities ranging from 2% to 57% were measured. The high opacities were usually obtained by reducing particulate control efficiencies. The data were compared with the acceptable standards of $\pm 7.5\%$ opacity deviation between observer and transmissometer used to certify observers of training plumes. The methods were within the $\pm 7.5\%$ opacity range of agreement for 19 of the tests (73% of the time). The observer measurements exceeded the transmissometer by more than 7.5% opacity in 3 tests (12% of the time), and were below the range in 4 tests (15% of the time). Two of the three higher observer readings were attributed to condensibility of plumes being measured, and one was attributed to interference by a near plume. Two of the lower observer readings were attributed to adverse viewing conditions. The reason for the two other opacity measurements was not apparent. In general, agreement of $\pm 10\%$ opacity may be expected between observer and transmissometer measurements when observer measurements are at the stack exit and plume visibility is good.

Particulate emissions from stationary sources are generally required to meet standards for both opacity and mass by air pollution regulatory agencies. The opacity standards are established primarily because they can be more easily monitored by control agencies and plant operators to determine that the operation and maintenance of emission control equipment are adequate. For this application of dual standards, the opacity standards established by the EPA are reportedly more lenient than the mass standards, thus, a violation of the opacity standard will be a clear indication of a violation of the mass standard.¹

The two most commonly used methods for measuring the opacity of particulate emissions are the trained observer and the in-stack transmissometers. To make the measurements, the trained observer stands at a designated distance from the smokestack and evaluates the opacity of the plume by observing its visual effects. For the transmissometer measure-

ments, the transmissometer is installed in the stack or duct to measure the transmission of light through the stack effluent as it flows past the instrument. The light transmission measurement is converted to an opacity measurement by subtracting the percentage of transmittance from 100%.

This paper describes a comparative study of opacity measurements by trained observer and in-stack transmissometers. The comparisons are of concurrent measurements made under field conditions at a variety of steady-state emission sources.

Experimental Methods

Opacity measurement by trained observer and in-stack transmissometer as described in the *Federal Register* by EPA^{1,2} are reviewed here and any deviations from these procedures are noted.

Opacity Measurements by Trained Observer

Trained observers are generally qualified by attending a visible emission training school and successfully passing a certification test. The training and certification program uses smoke generators from which black and white training plumes are generated under controlled conditions. The plumes are emitted from small stacks that contain light transmissometers for monitoring plume opacity. The observers are certified to evaluate the opacity of stack plumes after they demonstrate the capability to evaluate the opacity of the training plumes within a specified accuracy relative to the in-stack transmissometer readings.

When observing a plume, the EPA procedure (Test Method 9) requires that the observer stand (a) at a distance from the plume sufficient to provide a clear view of the emissions, (b) with his line of vision approximately perpendicular to the plume direction, and (c) with the sun oriented in the quadrant directly behind him. The method also requires that readings be made by observation of the plume momentarily at 15 s intervals over a 6 min period and at the point of greatest opacity; the average of these 24 readings is the observer's evaluation of the plume's opacity. All Method 9 guidelines were used for this study, except that the readings were always made on the plume approximately 0.5 stack diameters above the stack exit; also, observer evaluations were usually averages of more than

Table I. Opacity measurements and test conditions at various plants.

Test	Source	Stack		Transmissometer			Trained observer			Observer comments
		No.	Height/ width,m	Type ^a	Location	Opacity; % ^b	No. ^c	Time, min.	Opacity,% ^c	
1	Coal-fired power plant No. 1	1	76/3.4	S ¹	Duct	23 ± 10	1	6	25 ± *	Clear blue sky
2	Coal-fired power plant No. 1	2	76/3.4	S ¹	Duct	28 ± 4	1	6	20 ± *	Clear blue sky
3	Coal-fired power plant No. 1	3	76/4.1	S ¹	Duct	17 ± 7	1	6	15 ± *	Clear blue sky
4	Coal-fired power plant No. 2	4	244/7.3	S ¹	Duct	13 ± 1	2	10	8 ± 1	Clear blue sky
5	Coal-fired power plant No. 2	4	244/7.3	S ¹	Duct	23 ± 3	2	5	32 ± 1	Adj. plume interference
6	Coal-fired power plant No. 2	5	244/7.3	S ¹	Duct	10 ± 2	6	10	10 ± 1	Bright hazy sky
7	Coal-fired power plant No. 2	5	244/7.3	S ¹	Duct	30 ± 5	6	6	30 ± 2	Bright hazy sky
8	Coal-fired power plant No. 3	6	66/1.9	S	Stack	5 ± 1	3/4	11/11	0/0	Bright hazy sky
9	Coal-fired power plant No. 3	6	66/1.9	S	Stack	18 ± 3	3/4	17/17	0/0	Bright hazy sky
10	Coal-fired power plant No. 4	7	91/4.4	S	Stack	36 ± 2	5	15	30 ± 2	Clear broken clouds
11	Coal-fired power plant No. 5	8	178/4.7	S	Stack	13 ± 1	6	30	6 ± 1	Condensing plume
12	Coal-fired power plant No. 5	8	178/4.7	S	Stack	25 ± 2	6	30/30	25 ± 1/33 ± 1 ^f	Condensing plume
13	Coal-fired power plant No. 6	9	122/7.1	S	Stack	8 ± 0	6	15	11 ± 1	Clear broken clouds
14	Coal-fired power plant No. 6	9	122/7.1	S	Stack	20 ± 4	6	10	22 ± 1	Clear broken clouds
15	Coal-fired power plant No. 6	10	122/7.1	S	Stack	3 ± 0	6	15	10 ± 0	Condensing plumes
16	Coal-fired power plant No. 6	10	122/7.1	S	Stack	18 ± 2	6	7	23 ± 1	Condensing plume
17	Oil-fired power plant No. 1	11	153/5.2	P	Duct	19 ± 2	6	34	27 ± 1	Condensing plume
18	Oil-fired power plant No. 1	11	153/5.2	P	Duct	20 ± 2	6	22	30 ± 1	Condensing plume
19	Oil-fired power plant No. 2	12	46/3.3	P	Stack	7 ± 2	5	23	7 ± 1	Clear blue sky
20	Oil-fired power plant No. 3	13	60/3.0	P	Stack	3 ± 1	6	21	6 ± 1	Clear blue sky
21	Portland cement plant No. 1	14	76/4.6	P	Duct	14 ± 3	5/6	31/10	7 ± 1/5 ± 1 ^f	Clear sky near dusk
22	Portland cement plant No. 2	15	30/2.1	S	Stack	4 ± 1	7	55	0	Clear broken clouds
23	Portland cement plant No. 2	15	30/2.1	S	Stack	2 ± 1	7	5	0	Bright overcast
24	Paper mill (recovery furnace)	16	93/2.8	S	Stack	4 ± 0	5	22	4 ± 1	Clear blue sky
25	Phosphate plant (rock dryer)	17	25/2.0	P	Stack	28 ± 4	5/6	17/17	10 ± 1/9 ± 1 ^f	Clear blue sky
26	Phosphate plant (rock dryer)	17	25/2.0	P	Stack	57 ± 5	5/6	18/16	32 ± 1/33 ± 2 ^f	Clear blue sky

^a S¹ = Permanent transmissometers in dual ducts

S = Permanent transmissometers in stack or duct

P = Portable transmissometer in stack or duct

^b Mean ± range (estimated by visual inspection of chart)^c Specific observers are designated 1, 2, 3, 4, 5, 6, 7^d Mean ± 95% confidence interval of opacity measurements^e Range for opacity measurements not available^f Average of the two evaluations used for data analyses

24 readings taken over periods longer than 6 min. Six different trained observers were used during the study.

Opacity Measurements by In-Stack Transmissometer

The transmissometer is a well established instrument for monitoring particulate emissions that is required at certain sources by air pollution control agencies and EPA. In principle, the transmissometer for monitoring stack emissions is relatively simple. It consists of a lamp and collimating lens or reflector to project radiation from the lamp across the stack to a radiation detector. If the output from the transmissometer's detector is linear with respect to the incident radiation, its spectral response characteristics defined, and its projector and detector viewing angles restricted to small angles, then the transmittance of the emission at the defined wavelength is accurately measured by the transmissometer; it is simply the ratio of fluxes received at the detector with and without the emissions. For a more definitive discussion of design requirements for transmissometer opacity monitors, the report by Nader *et al.*³ is recommended. These design requirements were met by all of the transmissometers used in this study. The transmissometer opacity data were generated from three basic types of measurement:

- (1) across-stack or duct by permanently installed transmissometers;
- (2) in-stack or duct by portable transmissometer;
- (3) across dual ducts by permanently installed transmissometers.

In all cases, whenever the pathlength of the opacity monitor was different from the stack exit diameter, the opacity measurement was adjusted to a pathlength equal to the stack exit diameter. In the case of measurement type (3) above, where transmissometers were located in two ducts leading to a common stack, the duct flows were assumed equal and each transmissometer output was adjusted to a pathlength equal

to the stack exit diameter. Output data were then averaged to give a single opacity value for the plume.

Source and Test Description

Opacity measurements were made at 13 plants: 6 coal-fired power plants, 3 oil-fired power plants, 2 Portland cement plants, a kraft recovery furnace at a paper mill, and a rock dryer at a phosphate fertilizer plant. The majority of the plants were located in the southeastern U.S. Plants were chosen according to availability of in-stack opacity data; they were equipped either with their own transmissometers or with sampling ports for installation of portable transmissometers. Table I lists the various plants studied, the stack dimensions, type of transmissometer opacity measurements made, and location of the transmissometers. The table also lists specific observers, observation times, observer comments on viewing conditions, and opacity values determined by the two methods at the plants. When more than one set of measurements are shown for a plant, they were made on different stacks or on the same stack at different times and opacity levels. To prevent measurements from one stack from biasing the comparison, no more than two emission levels were studied or two data points generated from any one stack. A higher opacity level for a stack was obtained by turning off sections of ESP particulate emission control equipment.

Results and Discussion

A comparison of the opacity measurements by trained observer and in-stack transmissometer is shown in Figure 1. Also shown in the figure are the 1:1 line for perfect agreement between the data and lines for the ±7.5% deviation range. The ±7.5% opacity band represents the acceptable limits of deviation between plume measurements made by the observer and the in-stack transmissometer for observer certification on training plumes. The band is shown for these data only for

discussion purposes, and a presumption of accuracy by either method is not made.

The comparison shows that in the 26 tests, the data points in 19 showed agreement to within $\pm 7.5\%$ opacity, 4 showed observer measurements lower by more than 7.5% opacity, and 3 showed observer measurements higher by more than 7.5% opacity. Of the four lower observer measurements, two (Tests 8 and 21) were low, apparently because of a variable negative bias resulting from observer measurements taken under adverse environmental lighting and background conditions. The observers reported bright hazy sky or near dusk conditions for the tests. The variable negative bias (negative error) of the observer method when plumes are evaluated under adverse viewing conditions is recognized by EPA, and its significance with respect to the enforcement of opacity standards by trained observers is discussed in the *Federal Register* introduction to the method.¹

An example of variable negative bias and the effect of environmental conditions in the observer method can be seen in a study by Hamil *et al.*⁴ The authors obtained observer transmissometer opacity data at a coal-fired power plant from a series of tests conducted under three different environmental lighting and background conditions. Figure 2 shows regression lines of their data for the three test conditions and the impact of the different viewing conditions on the correlation. Observer opacity measurements became increasingly lower than transmissometer measurements as sky conditions became more overcast.

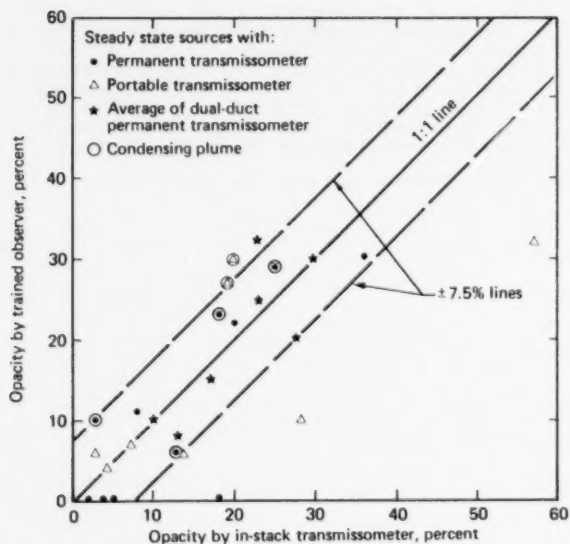


Figure 1. Plume opacity measured by trained observer and in-stack transmissometers.

The reason for the observer's lower readings at the phosphate fertilizer plant (Table I, Tests 25 and 26) is not apparent. It could not be attributed to poor plume lighting or background viewing conditions, because the two observers reported clear blue skies as the viewing conditions. However, since the two readings were low and appeared to represent negative observer error, their relevance for the enforcement of opacity standards by observers is the same as for low readings due to adverse environmental conditions. More significant to the enforcement of opacity standards by observers are the three higher observer measurements, because they represented potential positive error.

Two of the higher observer measurements were at an oil-fired power plant No. 1 (Tests 17 and 18) and the third was

at coal-fired power plant No. 2 (Test 5). At the oil-fired power plant, the observers noted that a condensable plume was forming as the effluent entered the atmosphere above the stack. This effluent contained gases at stack temperatures that condensed when it mixed with the cooler atmosphere. Thus, particles were formed in the stack plume, resulting in higher measurements of plume opacity. This condition was apparently produced by the high sulfur content of the fuel burned at the plant ($\sim 2.5\%$), which converted to sulfates and sulfuric acid in the effluent. Interestingly, condensable plumes were also noted by the observers during Tests 11, 12, 15 and 16, but

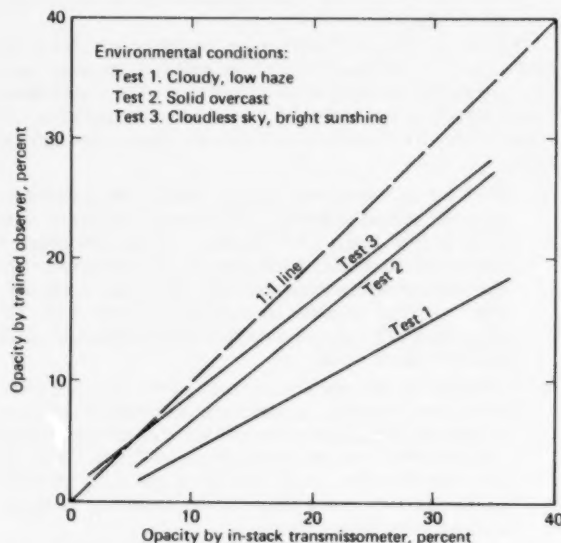


Figure 2. Linear regression relationships between plume opacity measurements by trained observer and in-stack transmissometer for different environmental conditions (Hamil *et al.* 1975).

their evaluations of the plumes at the stack exits were within 7.5% opacity of the in-stack opacity measurements, and in the case of Test 11, the observer's opacity measurement was lower than the in-stack measurement. The sky background viewing conditions for the condensable plume measurements were clear blue sky for Tests 11, 15 and 16, and hazy broken clouds for Tests 12, 17 and 18.

The observer's higher reading of the Test 5 coal-fired power plant could not be interpreted like Tests 17 and 18 since the plume was not condensable. Possibly, these results were produced by interference from an adjacent stack plume. The observer commented about the interference and indicated little confidence in the measurement. An earlier evaluation of a lower opacity plume from the same stack by the same observer without the interference was 5% lower opacity than the in-stack transmissometer measurement.

Conclusions

The data in this report do not provide information on the accuracy of either the transmissometer or observer opacity measurement methods, nor does disagreement between the methods show either method to be in error. This results because the measurements being compared are made on the stack effluent at two very different locations. The transmissometer measurements are within the stacks or ducts and the observer measurements are on the stack plumes. The opacity of an emission can vary from in-stack or duct and plume due to a variety of chemical reactions, coalescence of particles, and condensation of gases as the stack effluent temperature decreases.

The reader is reminded that the observer data in this report were collected under the constraint that they read plume opacities at the stack exits. Since the Method 9 procedure for visual determination of the opacity of visual emissions does not contain this constraint, caution should be used in drawing conclusions from the data about the use of in-stack transmissometer opacity measurements to determine compliance with emission opacity standards. However, it should also be noted that in practice the opacities of visible emissions are usually evaluated at stack exits by observers when determining compliance with emission opacity standards. Consequently, the results of the study do provide information on the applicability of in-stack transmissometers to monitoring opacity standards.

Within the observer viewing constraint noted above, the study provides information on how well the two most commonly used methods for measuring the opacity of stationary source emissions can be expected to agree when applied to real plants under field conditions. There are three major conclusions:

- Observer and transmissometer opacity measurements generally agreed to within $\pm 10\%$ opacity. Of the 26 tests made in this study, 23 (89%) were within 10% opacity. Agreement to within $\pm 10\%$ opacity was observed even when condensibles were observed above the stack, provided that the observer measurements were made between the stack exit and the condensible (within 0.5 stack diameter above stack).
- Observer opacity measurements can be expected to be lower than transmissometer measurements if the measurements are made when environmental and background viewing conditions cause poor plume visibility. Of the 26 tests made in this study, 3 (11%) of the observer measurements were lower than transmissometer measurement by more than 10% opacity.
- In no case did observer measurements exceed transmissometer measurements by more than 10% opacity.

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